XMM–Newton Observations of PSR J0538+2817 & PSR B1706–44

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OVERVIEW

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INTRODUCTION

- Of >1000 radio pulsars detected, <5% also found in X–rays

- X–ray pulsars represent a wide range of ages (10^3– 7 x 10^9 yrs), magnetic field strengths (10^8– 10^{13} G), periods (1.6 – 530 ms) and spectral properties

- Only a subset are suitable for observing thermal radiation from the NS surface

INTRODUCTION

– In pulsars >10^6 yr thermal emission from NS surface is not detectable: sharp reduction in surface temperature predicted when photon emission overtakes neutrino luminosity losses

– In pulsars <10^4 yr strong non–thermal radiation dominates

– Only in pulsars 10^4– 10^6 yr is the non–thermal component much fainter; hence thermal radiation from the NS surface can dominate at soft X–ray/UV energies

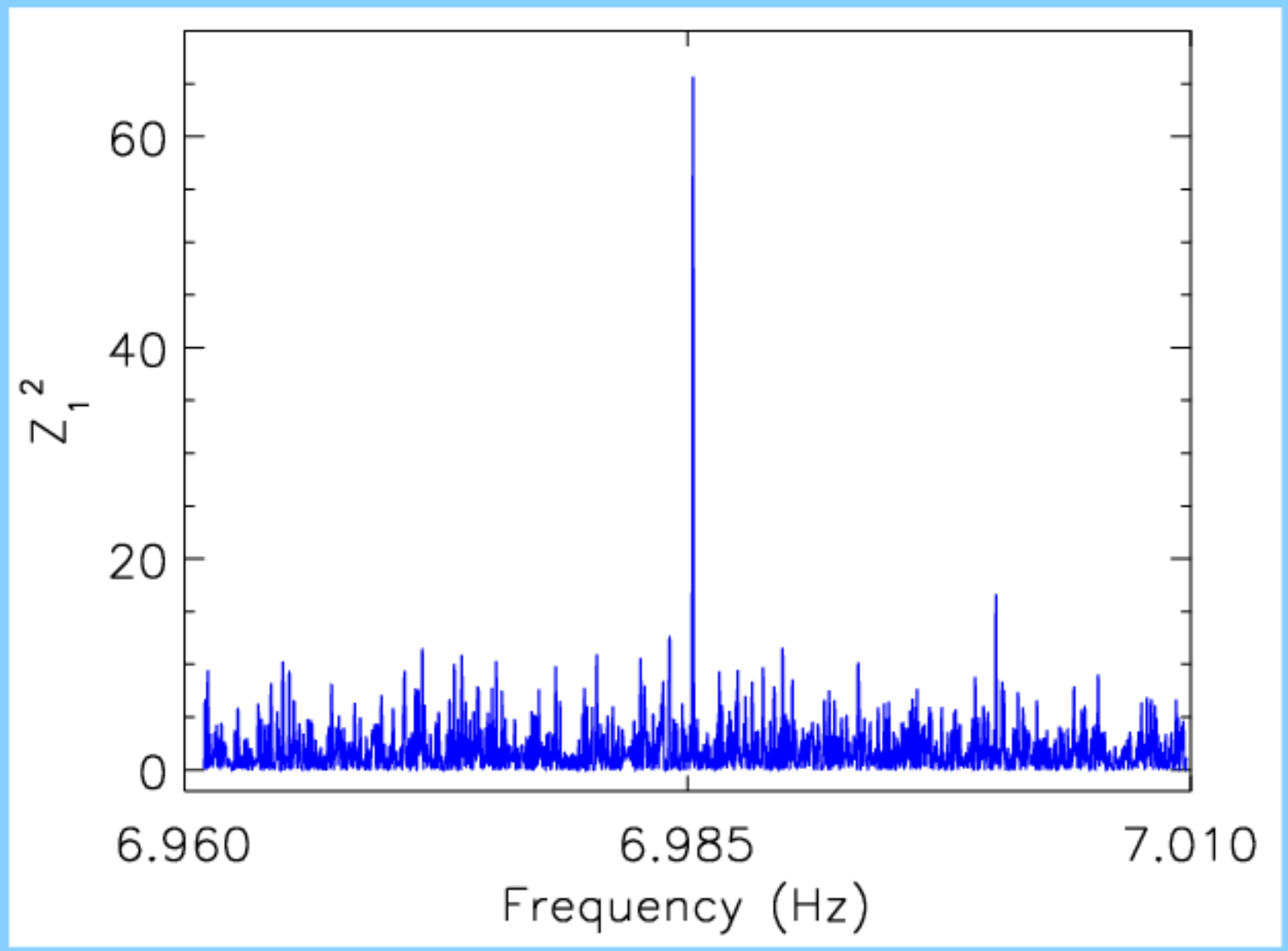
PSR J0538+2817

- P = 143 ms, spin–down age = 6 x 10^5 yr, D = 1.2 kpc
- Probably associated with supernova remnant S147
- Detected in X–rays with RASS, statistics not good enough to perform timing/spectral studies
- Marginal evidence for pulsed EGRET gamma–rays at radio period
- Three middle–aged pulsars, Geminga, B0656+14 & B1055–52, the "Three Musketeers", show NS surface thermal emission
- J0538+2817 has similar spin parameters to the "Musketeers" and is considered a good candidate for a gamma–ray pulsar, hence a dominant thermal component was expected

PSR J0538+2817 – Timing Analysis

– Observed for ~18 ks with XMM on 2002 March 8

– Peak at 6.9852548 Hz (P = 143.15870 ms) within errors consistent with radio frequency

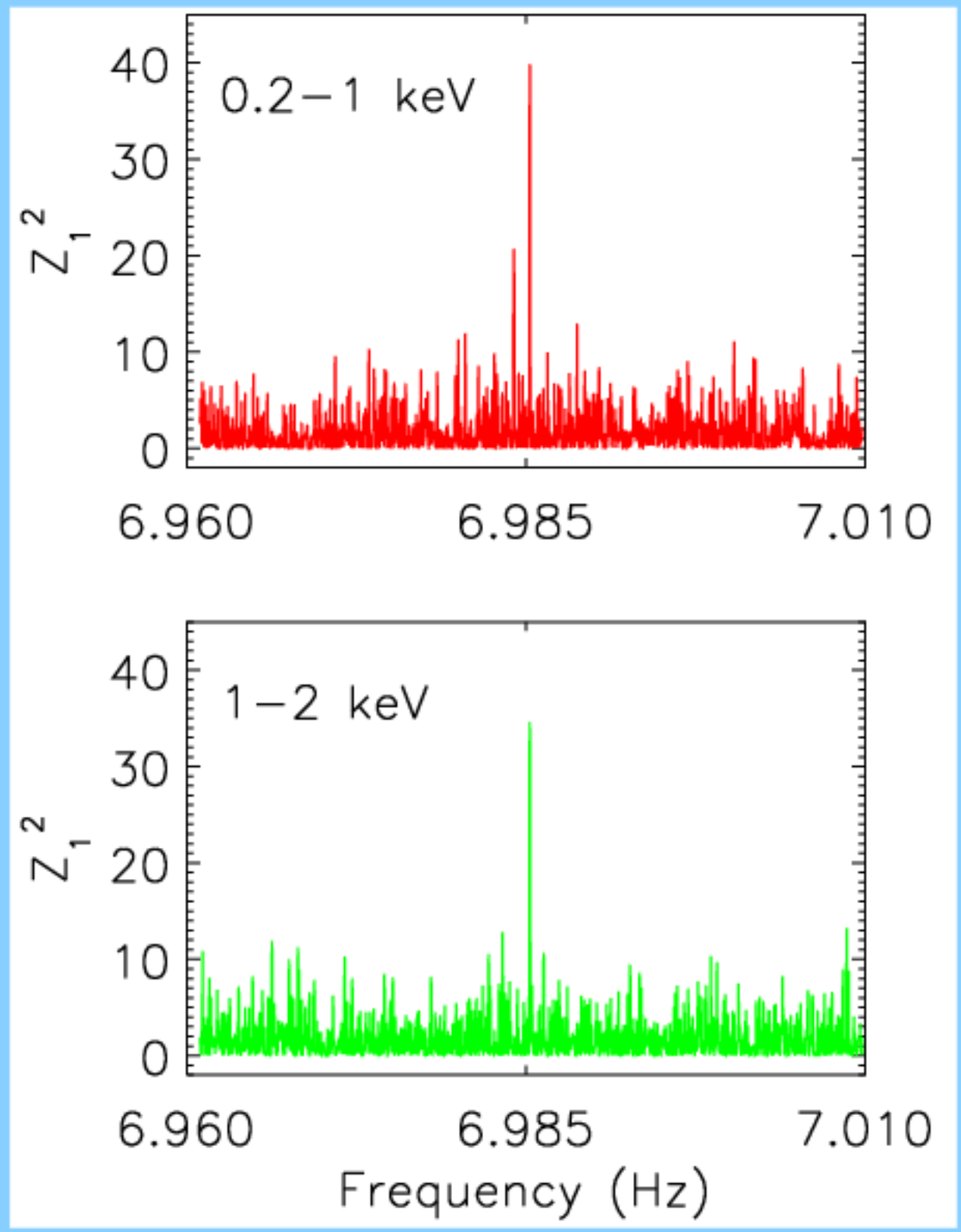


Z^2–statistic for peak is 65.57, with probability of chance occurrence of 5.5×10^{-15}

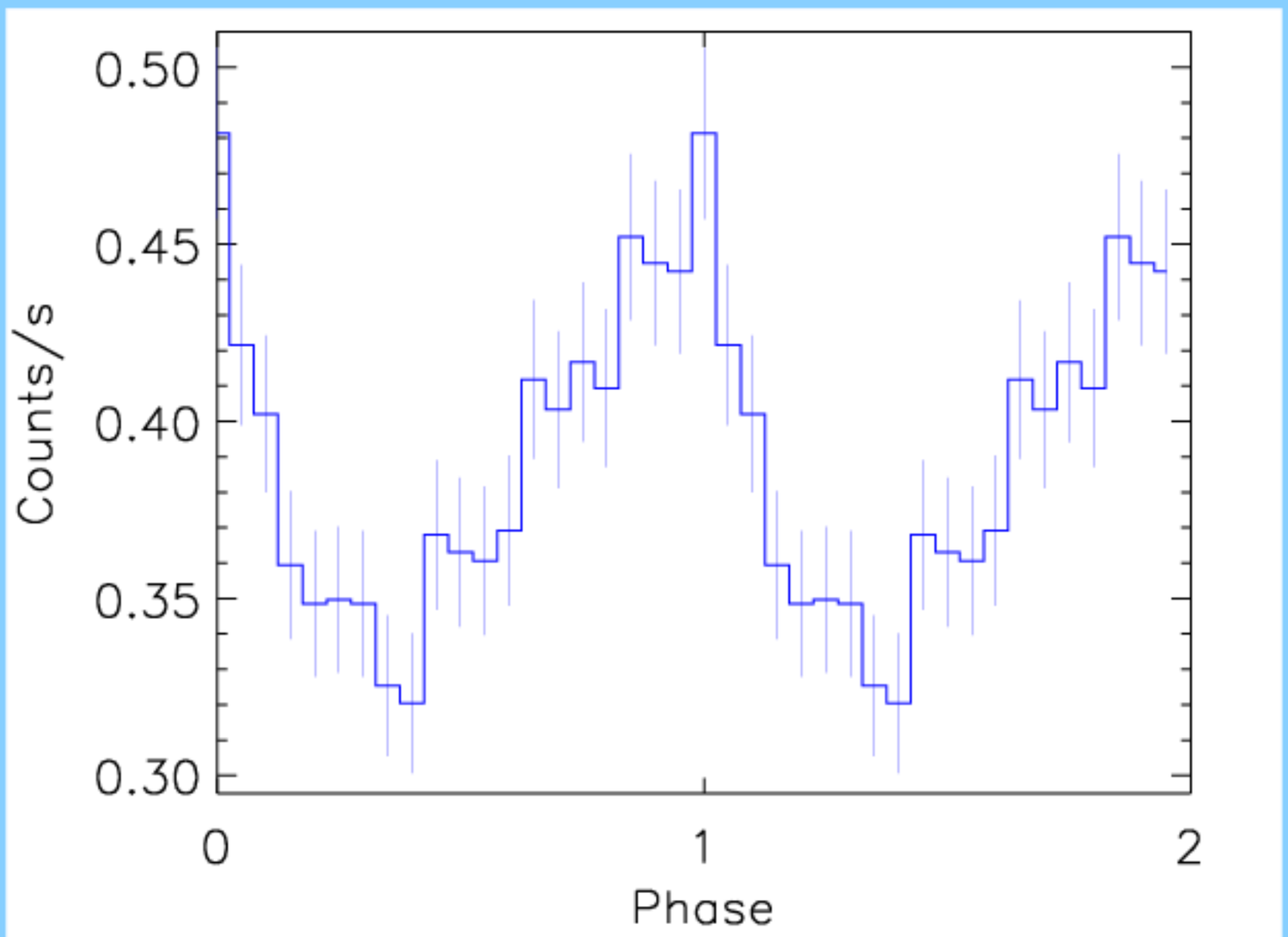
PSR J0538+2817 – Timing Analysis

– We can detect a pulsed signal in the 0.2 – 1 keV and 1 – 2 keV ranges

– At energies >2 keV we do not find a dominant peak in the periodograms near to the predicted radio frequency



PSR J0538+2817 – Folded Light Curve



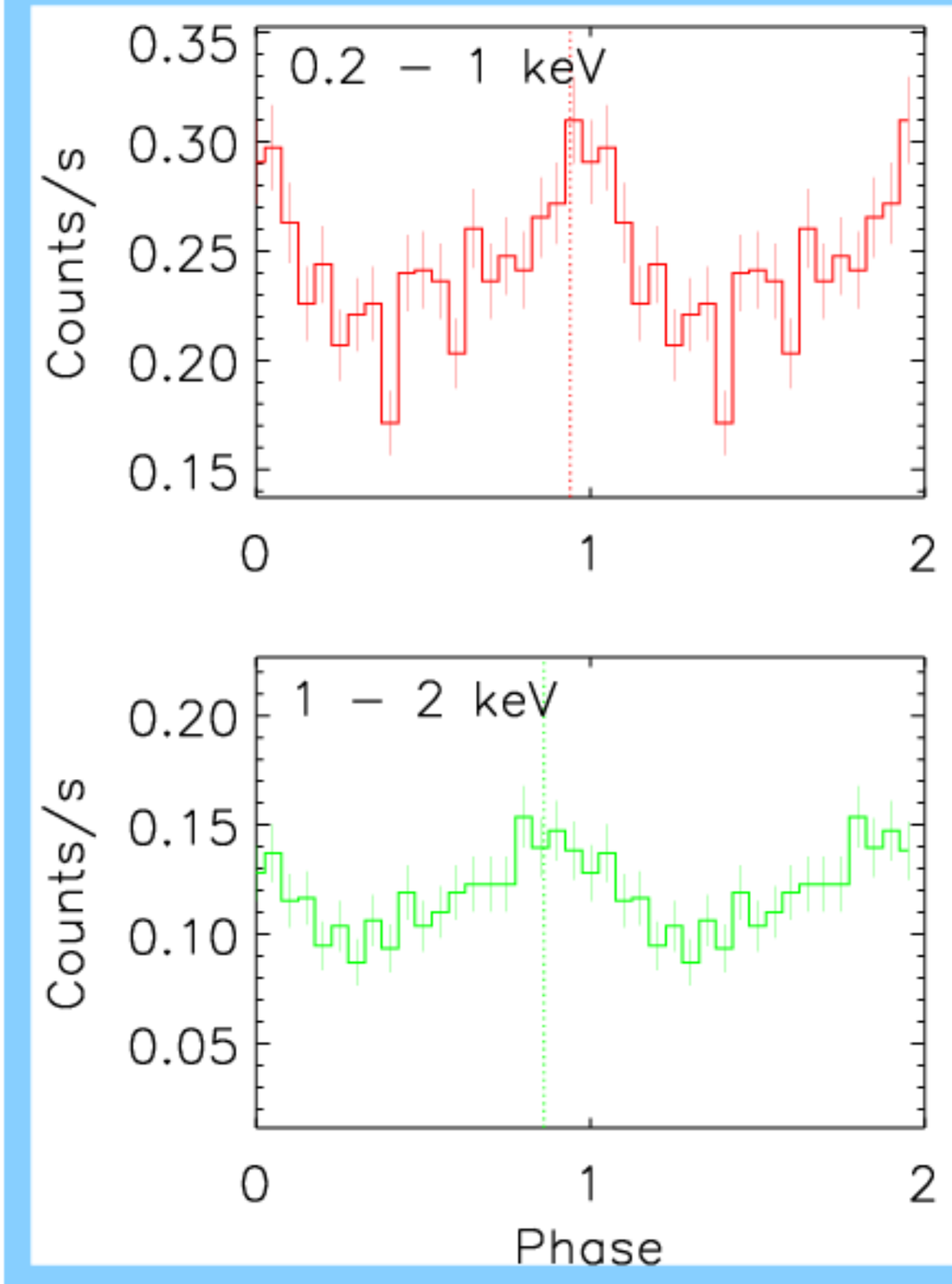
Folded light curve in 0.2 – 15 keV range

Pulse fraction is 18 +/– 3%

- **Pulse profile is asymmetric with a slower rise to and faster fall from maximum**
- **Arrival time of the radio pulse is consistent with the maximum of the X–ray peak**

PSR J0538+2817 – Folded Light Curve

– Light curves in 0.2 – 1 keV and 1 – 2 keV bands have pulse fractions of 30 +/– 3% and 27 +/– 3%



– Maximum in 0.2 – 1 keV band occurs at phase 0.94 +/– 0.05

– Maximum in 1 – 2 keV band occurs at phase 0.86 +/– 0.05

>> maxima in two bands are shifted by 0.08 in phase (pulse shift of 29°)

– But, uncertainty on the peak positions does not rule out zero phase shift

PSR J0538+2817 – Folded Light Curve

- Fit light curve with symmetrical polar cap model
- Input angular size of caps, angle between magnetic and rotation axes and angle between viewing direction and rotation axis
- Best fit : 20^{o}, 11^{o} and 31^{o} with $\chi^2_\nu = 1.71$, better than sinusoidal fit where $\chi^2_\nu = 4.0$
- But, polar cap model still falls short due to symmetry of model prediction
- Method limited given systematic differences between model and data, but can determine upper limit for the emitting region => pole cap size has to be constrained to a full angle of 65^{o}, otherwise observed pulsation cannot be reproduced

PSR J0538+2817 – Spectroscopy

- Source is ’middle–aged’, perhaps similar to the "Three Musketeers"
- B0656+14 and B1055–52 can be fit with two blackbodies (BB) and a power–law (PL), known as TS+TH+PL model
- PL due to non–thermal magnetospheric emission, 2 BBs are thermal components, one soft (TS) from most of the NS surface, and one hard (TH) from heated polar caps
- Geminga not bright enough to discriminate between the different thermal components, spectrum is well–fit with a BB+PL model

PSR J0538+2817 – Spectroscopy

- Fit spectrum of J0538+2817 with BB, PL, BB+PL, BB+BB, and the TS+TH+PL model, all modified by photoelectric absorption
- Multi–temperature models yield the same T for both components => only need one BB
- Large uncertainties on PL index indicate PL not required

PSR J0538+2817 – Spectroscopy

– Spectrum is well–fit with BB

$N_H = 2.51 \times 10^{21} cm^{-2}$

$T^{\infty} = (2.12^{+0.04}_{-0.03}) \times 10^6$ K

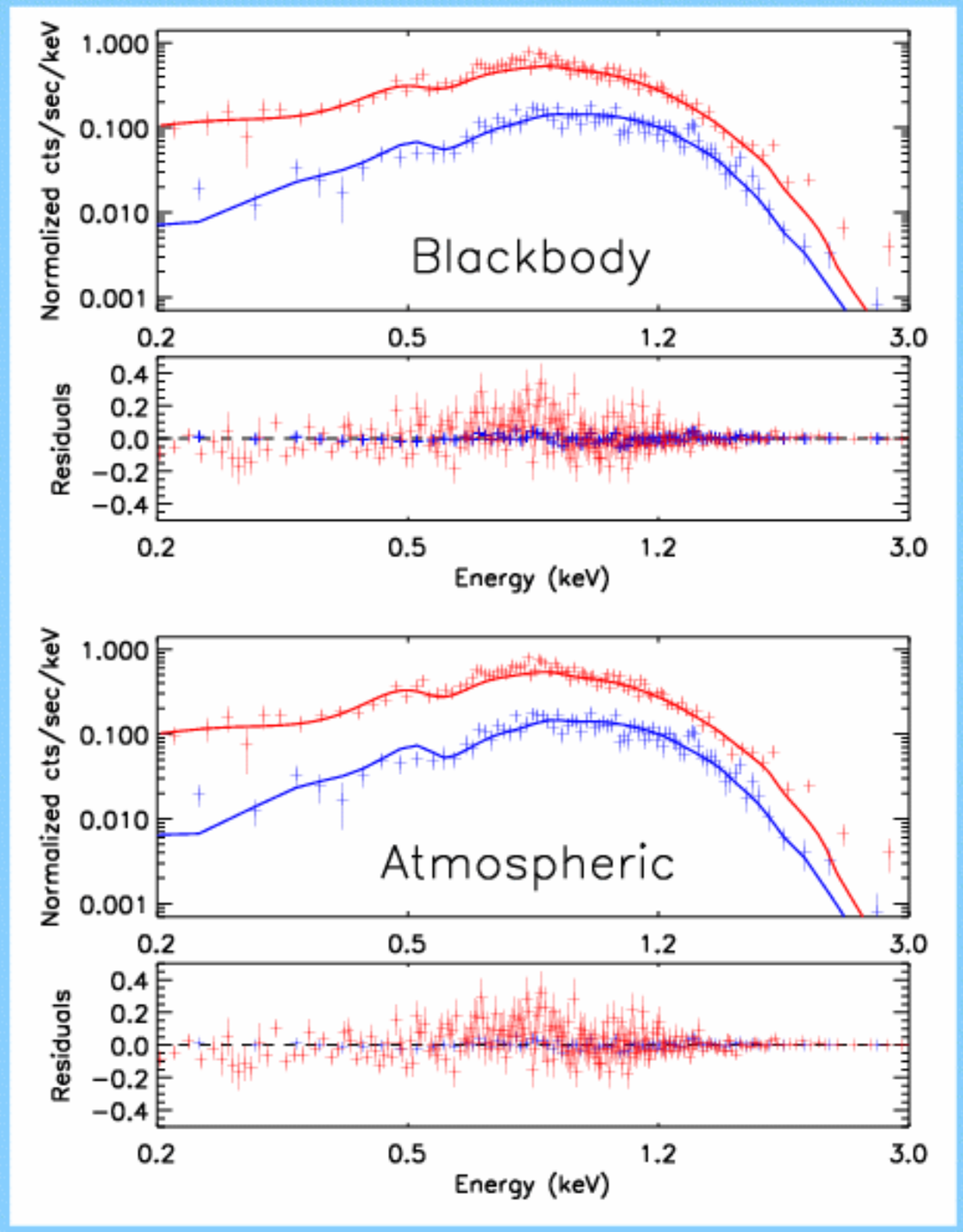
$\chi^2_\nu = 1.08$ for 321 d.o.f

$L_{0.1-2.4} = 4.0 \times 10^{32}$ erg/s

$L_{0.5-10} = 2.7 \times 10^{32}$ erg/s

$R^{\infty} = 1.68 +/- 0.05$ km

=> BB radius suggests emission from heated polar caps



PSR J0538+2817 – Spectroscopy

– Spectrum also well–fit with non–magnetic atmosphere model

$N_H = (4.18^{+0.01}_{-0.06}) \times 10^{21} cm^{-2}$

$T_{eff} = (0.68^{+0.10}_{-0.01}) \times 10^6 K$

χ^2_ν = 1.09 for 320 d.o.f

M_{NS} = 1.4 solar mass (fixed)

R_{NS} = 10 km (fixed)

– But distance to pulsar implied by fit is 0.26 kpc

– Need to fit with magnetic atmosphere model

PSR J0538+2817 – Conclusions

- First detection of pulsed X–rays at a frequency consistent with the predicted radio frequency
- Pulse profile is broad and asymmetric, with a pulse fraction of 18 +/– 3%
- Spectrum is well–fit with a single blackbody, questioning similarity to the "Three Musketeers"
- Radius determined from the fit of 1.68 +/– 0.05 km suggests emission is from a heated polar cap

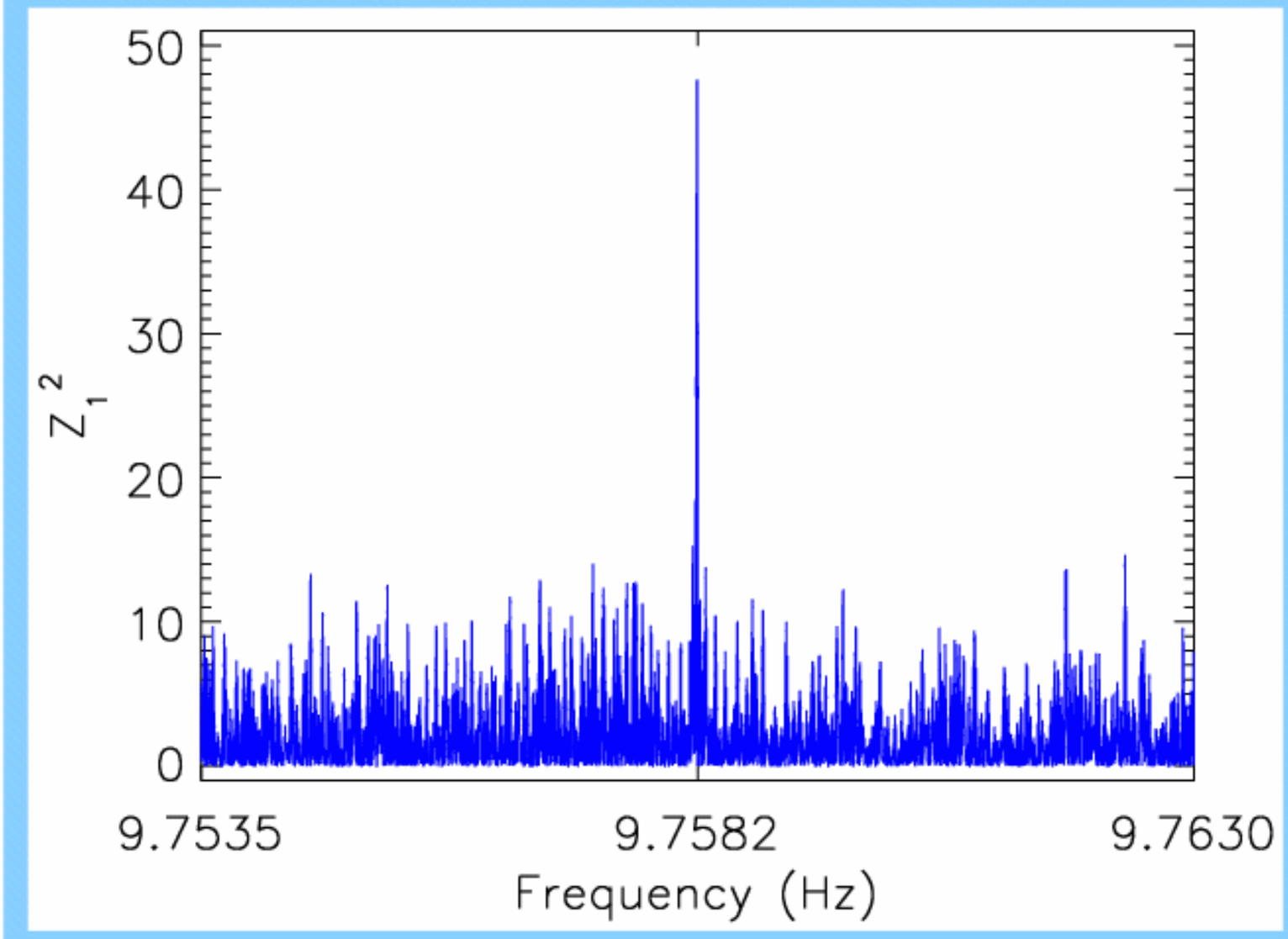
PSR B1706–44

- P = 102 ms, spin–down age = 1.7 x 10^4yr, D = 2.3 kpc
- "Vela–like" due to age/similar emission properties
- Displays glitches
- One of only 8 radio pulsars detected in GeV range, and one of 3 detected (marginal) in TeV range
- Evidence for 2 or 3 peaks in >400 MeV light curve, none of which are in phase with the radio peak
- Vela's gamma–ray light curve has 2 peaks, with at least 3 in X–rays
- Pulsed X–ray emission found in Chandra data
- Chandra spectrum fit with a BB+PL model
- BB radius of 3.6 +/– 0.9 km suggests emission from hot spot, or magnetic atmosphere model required

PSR B1706–44 – Timing Analysis

– Observed with XMM for ~40 ks and ~46 ks on 2002 March 12 and 13

– Peak at 9.7582270 Hz (P = 102.47763 ms)



Z^2 –statistic for peak is 47.64, with probability of chance occurrence of 4.5 x 10–11

PSR B1706–44 – Timing Analysis

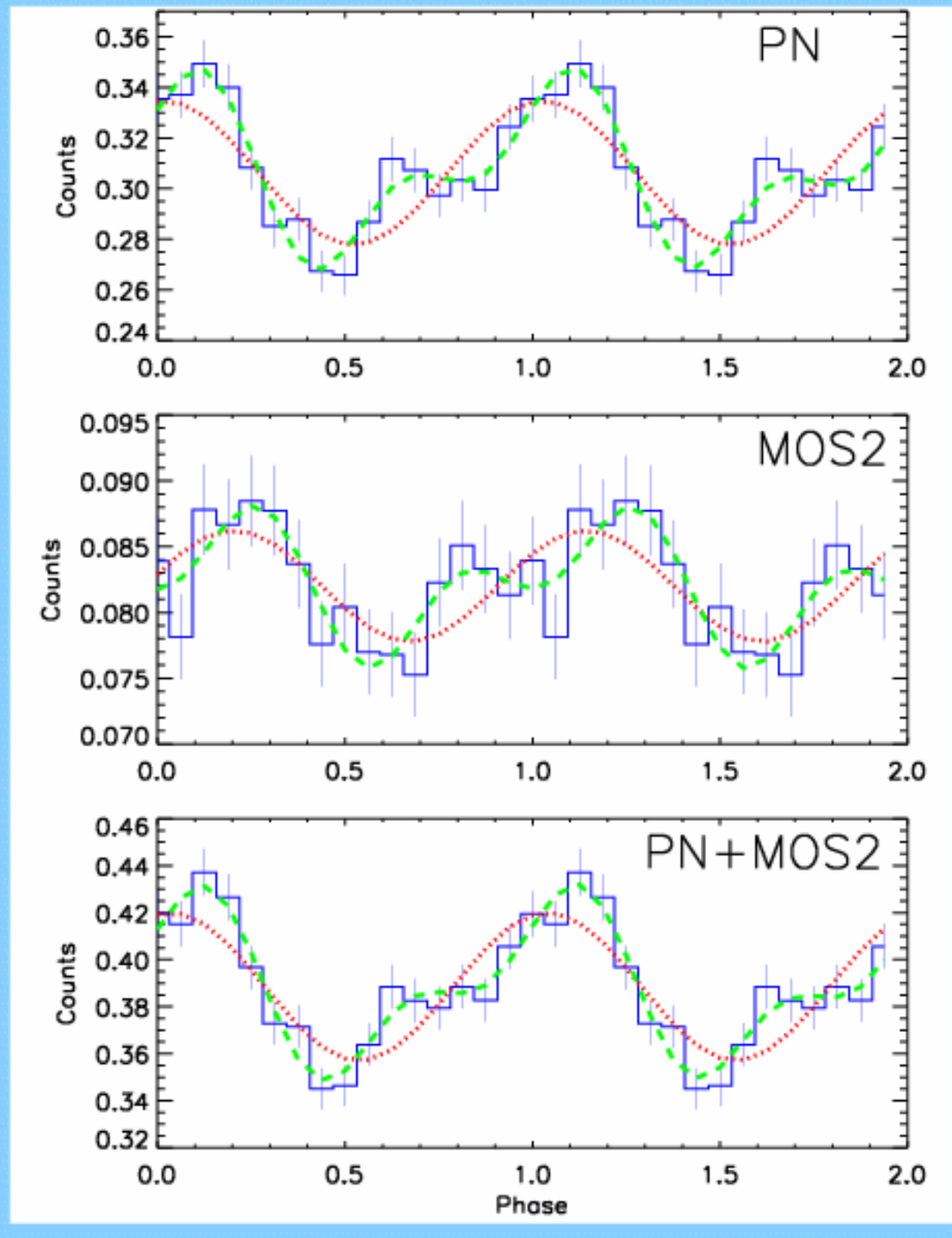
– Model folded light curves with one and 2 sinusoids

Data	ONE χ^2_ν[dof]	TWO χ^2_ν[dof]
P	2.98 [28]	0.81 [25]
M	0.94 [28]	0.56 [25]
P+M	2.41 [28]	0.73 [25]

– Fits to data are improved with 2 sinusoids model

– F–test indicates adding 2nd sinusoid is warranted in PN and PN+MOS2 cases

– Pulse fractions of two peaks are 9 +/– 3% and 18 +/– 4%



PSR B1706–44 – Spectroscopy

– Fit spectrum with thermal and PL models, modified by photoelectric absorption

– Fit with single BB is poor

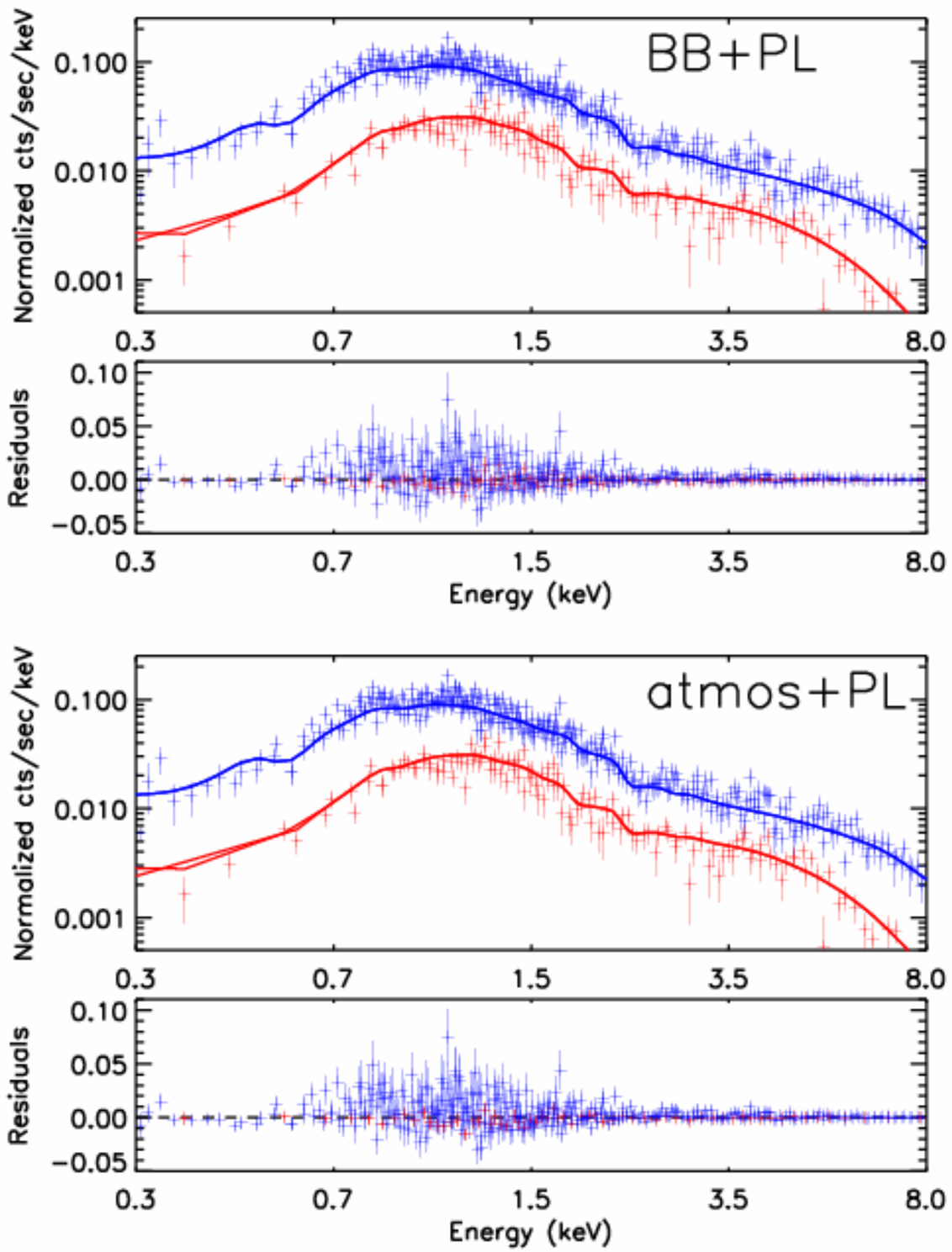
	BB+PL	Atmos+PL
N_H x 10^{21}cm^{-2}	$4.5^{+0.7}_{-0.4}$	$5.1^{+0.2}_{-0.1}$
Γ	$1.49^{+0.09}_{-0.08}$	$1.43^{+0.20}_{-0.05}$
R (km)	$1.81^{+0.43}_{-0.29}$	12 (fixed)
T x 10^6K	$2.01^{+0.18}_{-0.20}$	$0.82^{+0.01}_{-0.34}$
D (kpc)	2.3 +/– 0.3 (fixed)	2.1 +/– 0.2
χ^2_ν [dof]	0.84 [658]	0.84 [658]

PSR B1706–44 – Spectroscopy

– BB+PL model fits well, but size of emitting region too small to be compatible with whole NS

– Magnetic atmos+PL model fits well also, gives more physical description

PSR B1706–44 – Spectroscopy



– **Purely on a statistical basis we are unable to distinguish between the BB+PL and atmos+PL model fits**

– **Results indicate emission is either from whole NS with radius ~12 km or that the thermal X–rays are from a hot spot**

PSR B1706–44 – Conclusions

- Can resolve 2 peaks in X–ray light curve
- Similarities with Vela?
- Correlations between different wavelengths only established recently for Vela with 2 – 30 keV light curve
- The spectra of Vela, and the radio–silent NSs 1E 1207–52 and RX J0822–4300, are the only sources where the thermal component is better described by an atmospheric model
- Based on physical grounds, PSR B1706–44 is another example, with $R = 13.41^{+1.75}_{-4.84}$ km, compatible with size of NS